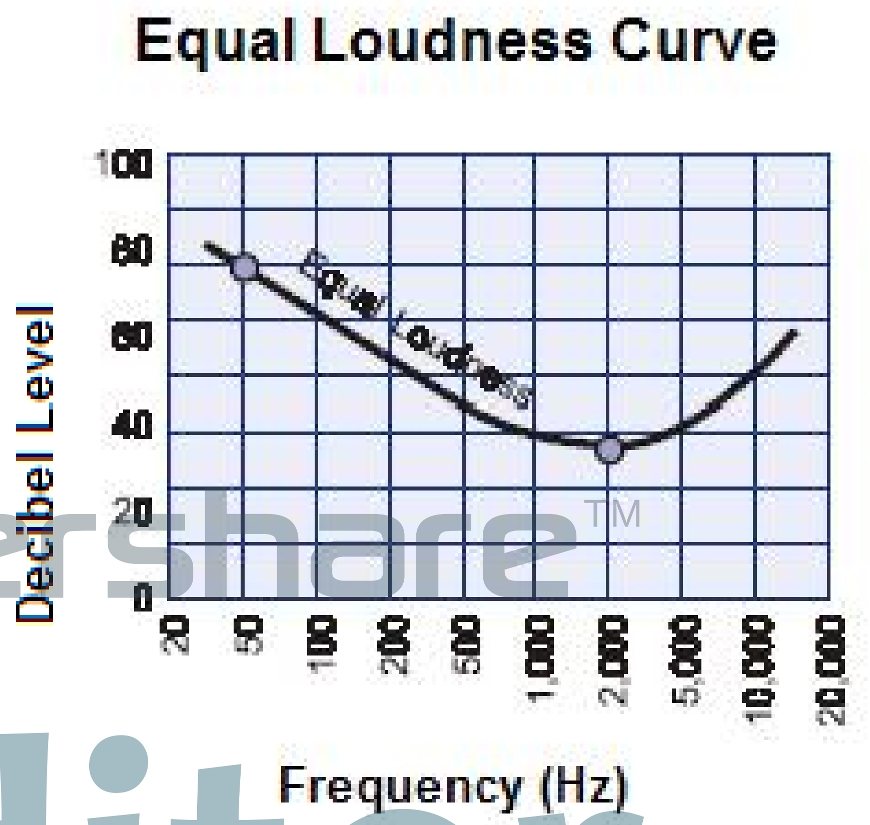
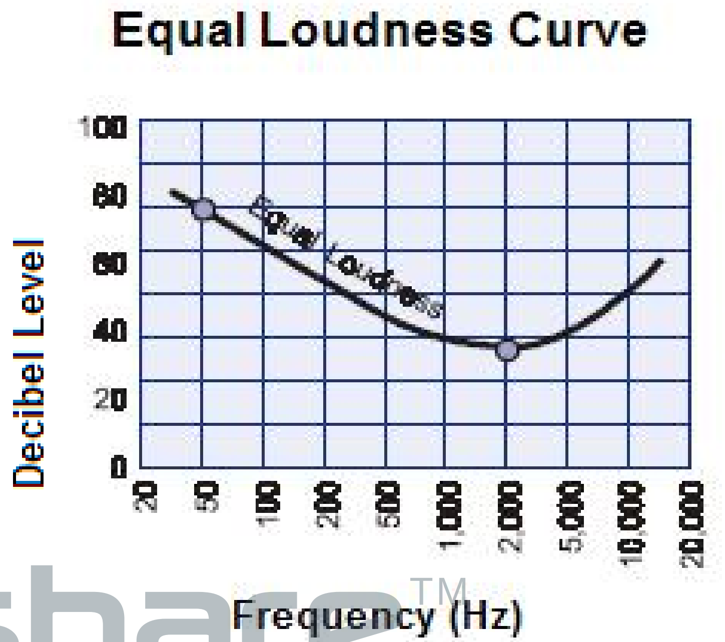
Sensitivity of the ear

- How we hear the loudness of sound is affected by the frequency of the sound as well as by the amplitude.
- The human ear is most sensitive to sounds between 300 and 3,000 Hz.
- The ear is less sensitive to sounds outside this range.
- Most of the frequencies that make up speech are between 300 and 3,000 Hz.



- The Equal Loudness Curve on the right shows how sounds of different frequencies compare. Sounds near 2,000 Hz seem louder than sounds of other frequencies, even at the same decibel level.
- For example, the Equal Loudness Curve shows that a 40 dB sound at 2,000 Hz sounds just as loud as an 80 dB sound at 50 Hz.



- **Sound waves are divided into three categories that cover different frequency ranges:**

a) Audible waves lie within the range of sensitivity of the human ear. They can be generated in a variety of ways, such as by musical instruments, human voices, or loudspeakers.

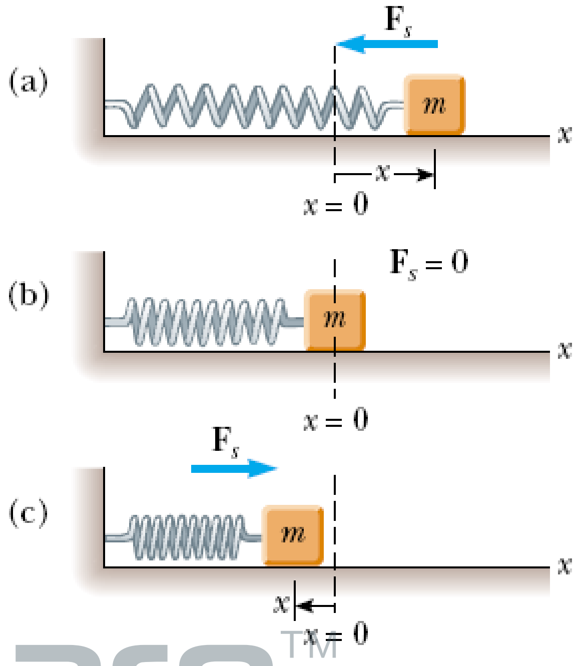
b) Infrasonic waves have frequencies below the audible range. Elephants can use infrasonic waves to communicate with each other .

c) Ultrasonic waves have frequencies above the audible range.

Motion of an Object Attached to a spring

- when the block is displaced to a position x, the spring exerts on the block a force that is proportional to the position and given by Hooke's law

$$F_s = -kx$$



- We call this a restoring force because it is always directed toward the equilibrium position and therefore *opposite the displacement from equilibrium*.

- Applying Newton's second law $\Sigma F_x = m_a x$ to the motion of the block, we obtain

$$-kx = ma_x$$

$$a_x = -\frac{k}{m}x$$

That is, the acceleration is proportional to the position of the block, and its direction is opposite the direction of the displacement from equilibrium.

Systems that behave in this way are said to exhibit simple harmonic motion. An object moves with simple harmonic motion whenever its acceleration is proportional to its position and is oppositely directed to the displacement from equilibrium.

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Mathematical Representation of Simple Harmonic Motion

by definition, we can represent $a = dv/dt = d^2x/dt^2$, and so we can express

$$\frac{d^2x}{dt^2} = -\frac{k}{m}x$$

If we denote the ratio k/m with the symbol ω^2 then

$$\omega^2 = \frac{k}{m}$$

$$\frac{d^2x}{dt^2} = -\omega^2 x \qquad \textbf{6.5}$$

What we now require is a mathematical solution to **6.5**

$$x(t) = A\cos(\omega t + \phi)$$

where A, ω, and φ are constants. To see explicitly that this equation satisfies Equation 6.5, note that

$$\frac{dx}{dt} = A\frac{d}{dt}\cos(\omega t + \phi) = -\omega A\sin(\omega t + \phi) \qquad 6.7$$

$$\frac{d^2x}{dt^2} = -\omega A\frac{d}{dt}\sin(\omega t + \phi) = -\omega^2 A\cos(\omega t + \phi) \qquad 6.8$$

Comparing Equations 6.6 and 6.8, we see that $d^2x/dt^2 = -\omega^2 x$ and Equation 6.5 is satisfied.

Wave Motion

- Consider a pulse traveling to the right on a long string, the shape of the pulse, whatever it may be, can be represented by some mathematical function which we will write as $y(x, 0) = f(x)$.
- This function describes the transverse position y of the element of the string located at each value of x at time $t = 0$.

- Because the speed of the pulse is *v*, the pulse has traveled to the right a distance *vt* at the time *t* (Fig. 7.1b). We assume that the shape of the pulse does not change with time. Thus, at time *t*, the shape of the pulse is the same as it was at time $t = 0$, as in Figure 7.1a.

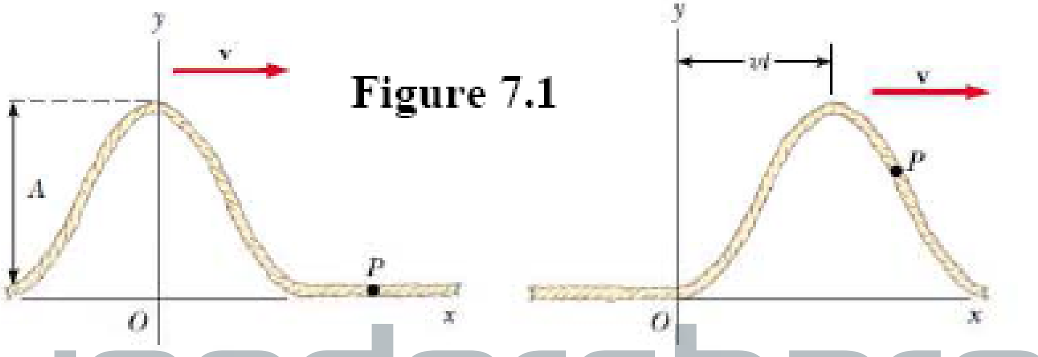


Figure 7.1

(a) Pulse at $t = 0$ (b) Pulse at time t

A one-dimensional pulse traveling to the right with a speed v. (a) At $t = 0$, the shape of the pulse is given by $y = f(x)$. (b) At some later time t, the shape remains unchanged and the vertical position of an element of the medium any point P is given by $y = f(x - vt)$.

- Consequently, an element of the string at x at this time has the same y position as an element located at x - vt had at time t = 0:

$$y(x, t) = y(x - vt, 0)$$

Similarly, if the pulse travels to the left, the transverse positions of elements of the string are described by

$$y(x, t) = f(x + vt)$$

The function *y, sometimes called the wave function, depends on the two variables x and t. For this reason, it is often written y(x, t), which is read “y as a function of x* and *t.”*

Sinusoidal Waves

- we introduce an important wave function whose shape is sinusoidal called sinusoidal wave as in Figure 7.2a, which shows the position of the wave at t = 0. Because the wave is sinusoidal, we expect the wave function at this instant to be expressed as $y(x, 0) = A \sin ax$, where A is the amplitude and a is a constant to be determined. At $x = 0$, we see that $y(0, 0) = A \sin a(0) = 0$, consistent with Figure 7.2a. The next value of x for which y is zero is $x = \lambda/2$. Thus,

$$y\left(\frac{\lambda}{2}, 0\right) = A \sin a\left(\frac{\lambda}{2}\right) = 0 \qquad 7.4$$

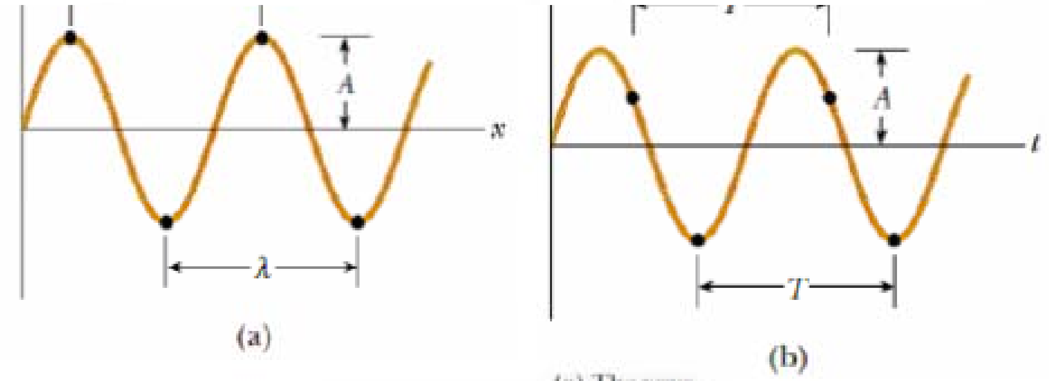


Figure 7.2 (a) The wavelength λ of a wave is the distance between adjacent crests or adjacent troughs. (b) The period *T* of a wave is the time interval required for the wave to travel one wavelength.

For this to be true, we must have $a(\lambda/2) = \pi$, or $a = 2\pi/\lambda$. Thus, the function describing the positions of the elements of the medium through which the sinusoidal wave is traveling can be written

$$y(x, 0) = A \sin\left(\frac{2\pi}{\lambda} x\right)$$

If the wave moves to the right with a speed v, then the wave function at some later time t is

$$y(x, t) = A \sin\left[\frac{2\pi}{\lambda}(x - vt)\right]$$

By definition, the wave travels a distance of one wavelength in one period T. Therefore, the wave speed, wavelength, and period are related by the expression

$$v = \frac{\lambda}{T} \qquad 7.7$$

- The variation in the gas pressure ΔP measured from the equilibrium value is also periodic.

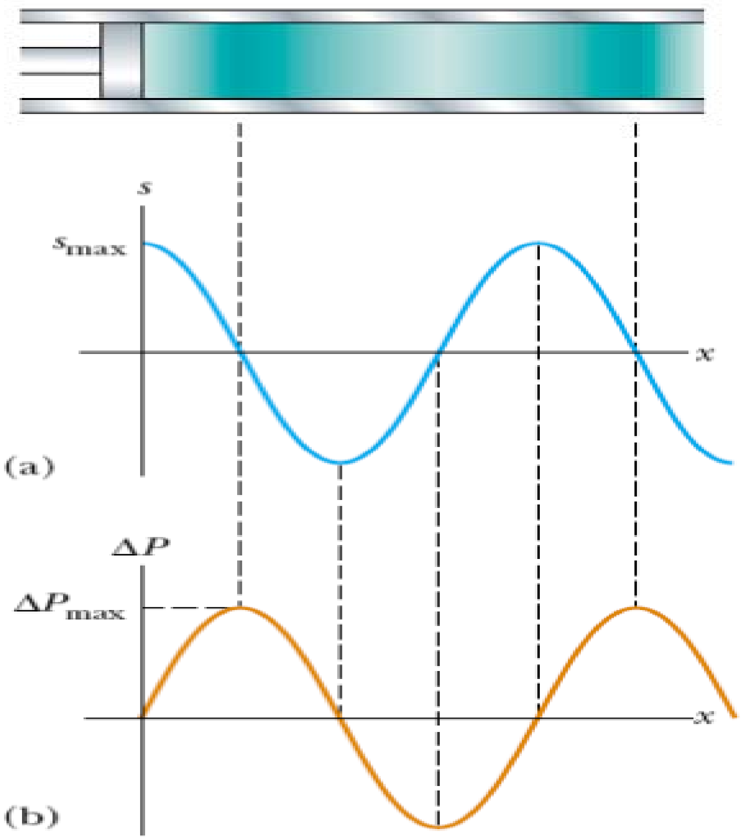
$$\Delta P = \Delta P_{\max} \sin(kx - \omega t) \qquad (2)$$

- where the pressure amplitude $\Delta P_{\max}$—which is the maximum change in pressure from the equilibrium value—is given by

$$\Delta P_{\max} = \rho v \omega s_{\max} \qquad (3)$$

- Thus, we see that a sound wave may be considered as either a displacement wave or a pressure wave. A comparison of their equation shows that the pressure wave is 90° out of phase with the displacement wave..

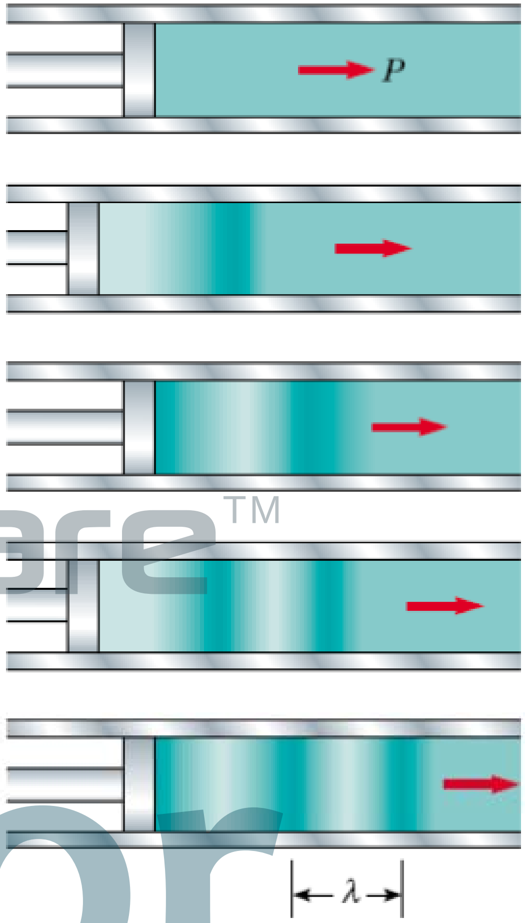
- Graphs of these functions are shown in. Note that the pressure variation is a maximum when the displacement from equilibrium is zero, and the displacement from equilibrium is a maximum when the pressure variation is zero



Derivation of Pressure Equation

Consider a thin disk-shaped element of gas whose circular cross section is parallel to the piston in Figure. This element will undergo changes in position, pressure, and density as a sound wave propagates through the gas.

From the definition of bulk modulus



$$B \equiv \frac{\text{volume stress}}{\text{volume strain}} = -\frac{\Delta F/A}{\Delta V/V_i} = -\frac{\Delta P}{\Delta V/V_i}$$

The pressure variation in the gas is

$$\Delta P = -B\frac{\Delta V}{V_i} \qquad (4)$$

- The element has a thickness Δx in the horizontal direction and a cross-sectional area A, so its volume is $V_i = A\Delta x$.

- The change in volume ΔV accompanying the pressure change is equal to $A\Delta s$, where Δs is the difference between the value of s at $x + \Delta x$ and the value of s at x. Hence, we can express ΔP as

$$\Delta P = -B\frac{\Delta V}{V_i} = -B\frac{A\Delta s}{A\Delta x} = -B\frac{\Delta s}{\Delta x} \qquad (5)$$

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As Δx approaches zero, the ratio $\Delta s/\Delta x$ becomes $\partial s/\partial x$. (The partial derivative indicates that we are interested in the variation of s with position at a *fixed* time.) Therefore,

$$\Delta P = -B\frac{\partial s}{\partial x}$$

- If the position function is the simple sinusoidal function given before, we find that

$$\Delta P = -B\frac{\partial}{\partial x}[s_{\max}\cos(kx - \omega t)] = Bs_{\max}k\sin(kx - \omega t) \qquad (6)$$

Because the bulk modulus is given by $B = \rho v^2$ seen before, the pressure variation reduces to

$$\Delta P = \rho v^2 s_{\max} k \sin(kx - \omega t)$$

we can write $k = \omega/v$; hence, ΔP can be expressed as

$$\Delta P = \rho v \omega s_{\max} \sin(kx - \omega t) \qquad (7)$$

- Because the sine function has a maximum value of 1, we see that the maximum value of the pressure variation is $\Delta P_{\max} = \rho v \omega s_{\max}$ and we arrive to

$$\Delta P = \Delta P_{\max} \sin(kx - \omega t) \qquad (8)$$

QUIZ

- As a certain sound wave travels through the air, it produces pressure variations (above and below atmospheric pressure) given by

$\Delta P = 1.27 \sin(\pi x - 340\pi t)$ in SI units. Find

(a) the amplitude of the pressure variations,

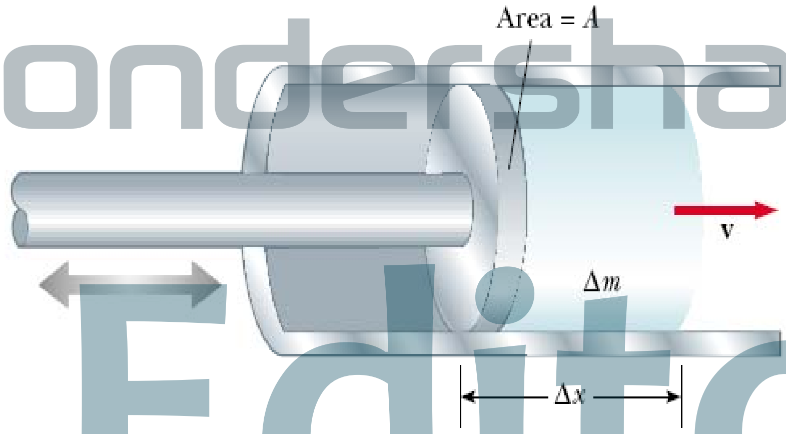
(b) the frequency,

(c) the wavelength in air, and

(d) the speed of the sound wave.

Intensity of Periodic Sound Waves

- we showed that a wave traveling on a taut string transports energy. The same concept applies to sound waves. Consider an element of air of mass Δm and width Δx in front of a piston oscillating with a frequency ω, as shown in Figure below.



- The piston transmits energy to this element of air in the tube, and the energy is propagated away from the piston by the sound wave.
- To evaluate the rate of energy transfer for the sound wave, we shall evaluate the kinetic energy of this element of air, which is undergoing simple harmonic motion.
- We shall follow a procedure in which we evaluated the rate of energy transfer for a wave on a string.
- As the sound wave propagates away from the piston, the position of any element of air in front of the piston is given by Equation (1).

$$s(x, t) = s_{\max} \cos(kx - \omega t)$$

- To evaluate the kinetic energy of this element of air, we need to know its speed. We find the speed by taking the time derivative of Equation (1):

$$\boxed{v(x, t) = \frac{\partial}{\partial t} s(x, t) = \frac{\partial}{\partial t}[s_{\max} \cos(kx - \omega t)] = -\omega s_{\max} \sin(kx - \omega t)}$$

Imagine that we take a "snapshot" of the wave at $t = 0$. The kinetic energy of a given element of air at this time is

$$\Delta K = \tfrac{1}{2}\Delta m(v)^2 = \tfrac{1}{2}\Delta m(-\omega s_{\max} \sin kx)^2 = \tfrac{1}{2}\rho A\, \Delta x(-\omega s_{\max} \sin kx)^2$$

$$= \tfrac{1}{2}\rho A\, \Delta x(\omega s_{\max})^2 \sin^2 kx$$

where A is the cross-sectional area of the element and $A\Delta x$ is its volume. We integrate this expression over a full wavelength to find the total kinetic energy in one wavelength. Letting the element of air shrink to infinitesimal thickness,

so that $\Delta x \rightarrow dx$, we have

$$K_\lambda = \int dK = \int_0^\lambda \tfrac{1}{2}\rho A(\omega s_{\max})^2 \sin^2 kx\,dx = \tfrac{1}{2}\rho A(\omega s_{\max})^2 \int_0^\lambda \sin^2 kx\,dx$$

$$= \tfrac{1}{2}\rho A(\omega s_{\max})^2(\tfrac{1}{2}\lambda) = \tfrac{1}{4}\rho A(\omega s_{\max})^2\lambda$$

Since $\sin^2 x = \frac{1}{2} - \frac{1}{2}\cos(2x)$

Therefore $\sin^2 kx = \frac{1}{2} - \frac{1}{2}\cos(2kx)$

By substitution in the integration

$$\int_0^{\lambda} \sin^2 kx = \int_0^{\lambda} {}^{1}\!/_{2} - {}^{1}\!/_{2} \cos(2kx)$$

$$= \left(\frac{1}{2}\lambda\right) - {}^{1}\!/_{2} \left[\sin 2k\lambda - \sin 0\right]$$

$$\sin ce \quad k = \left(\frac{\omega}{v}\right)\lambda \quad \mathit{and} \quad \sin ce \quad v = \lambda\omega$$

$$\therefore \int_0^{\lambda} \sin^2 kx = \int_0^{\lambda} {}^{1}\!/_{2} - {}^{1}\!/_{2} \cos(2kx)$$

$$= \left(\frac{1}{2}\lambda\right) - {}^{1}\!/_{2} \left[\sin 2\left(\frac{\omega}{\lambda\omega}\right)\lambda - \sin 0\right]$$

$$= \left(\frac{1}{2}\lambda\right) - {}^{1}\!/_{2} \left[\sin 2 - \sin 0\right]$$

$$= \left(\frac{1}{2}\lambda\right) \quad \sin ce \quad \sin 2 \approx \sin 0$$

- The total potential energy for one wavelength has the same value as the total kinetic energy; thus, the total mechanical energy for one wavelength is

$$E_\lambda = K_\lambda + U_\lambda = \tfrac{1}{2}\rho A(\omega s_{\max})^2\lambda$$

The rate of energy transfer is

$$\mathcal{P} = \frac{\Delta E}{\Delta t} = \frac{E_\lambda}{T} = \frac{\frac{1}{2}\rho A(\omega s_{\max})^2\lambda}{T} = \tfrac{1}{2}\rho A(\omega s_{\max})^2\left(\frac{\lambda}{T}\right) = \tfrac{1}{2}\rho A v(\omega s_{\max})^2$$

where *v* is the speed of sound in air.

We define the **intensity** *I* of a wave, or the power per unit area, to be the rate at which the energy being transported by the wave transfers through a unit area *A* perpendicular to the direction of travel of the wave:

$$I \equiv \frac{\mathcal{P}}{A}$$

In the present case, therefore, the intensity is

$$I = \frac{\mathcal{P}}{A} = \frac{1}{2}\rho v(\omega s_{\max})^2$$

Thus, we see that the intensity of a periodic sound wave is proportional to the square of the displacement amplitude and to the square of the angular frequency

This can also be written in terms of the pressure amplitude $\Delta P_{\max}$; in this case, we obtain

$$I = \frac{\Delta P_{\max}^2}{2\rho v}$$

- Now consider a point source emitting sound waves equally in all directions. From everyday experience, we know that the intensity of sound decreases as we move farther from the source.
- We identify an imaginary sphere of radius r centered on the source.
- When a source emits sound equally in all directions, we describe the result as a spherical wave. The average power P_{av} emitted by the source must be distributed uniformly over this spherical surface of area $4\pi r^2$. Hence, the wave intensity at a distance r from the source is

$$I = \frac{\mathcal{P}_{\mathrm{av}}}{A} = \frac{\mathcal{P}_{\mathrm{av}}}{4\pi r^2}$$

This inverse-square law, which is reminiscent of the behavior of gravity, states that the intensity decreases in proportion to the square of the distance from the source.

Example

- A point source emits sound waves with an average power output of 80.0 W.

(A) Find the intensity 3.00 m from the source.

(B) Find the distance at which the intensity of the sound is 1.00×10^{-8} W/m^2.

Solution A point source emits energy in the form of spherical waves. Using Equation 17.7, we have

$$I = \frac{\mathcal{P}_{\text{av}}}{4\pi r^2} = \frac{80.0\text{ W}}{4\pi(3.00\text{ m})^2} = \boxed{0.707\text{ W/m}^2}$$

an intensity that is close to the threshold of pain.

$$r = \sqrt{\frac{\mathcal{P}_{\text{av}}}{4\pi I}} = \sqrt{\frac{80.0\text{ W}}{4\pi(1.00 \times 10^{-8}\text{ W/m}^2)}}$$

$$= \boxed{2.52 \times 10^4\text{ m}}$$

which equals about 16 miles!

QUIZ

- **A vacuum cleaner produces sound with a measured sound level of 70.0 dB. (a) What is the intensity of this sound in W/m^2? (b) What is the pressure amplitude of the sound?**

Given : The speed of sound in air is 340m/s and the density of air is 1.2 Kg/m^3

Solution

(a) $$70.0\text{ dB} = 10\log\left(\frac{I}{1.00\times10^{-12}\ \text{W/m}^2}\right)$$

Therefore, $I = \left(1.00\times10^{-12}\ \text{W/m}^2\right)10^{(70.0/10)} = \boxed{1.00\times10^{-5}\ \text{W/m}^2}$.

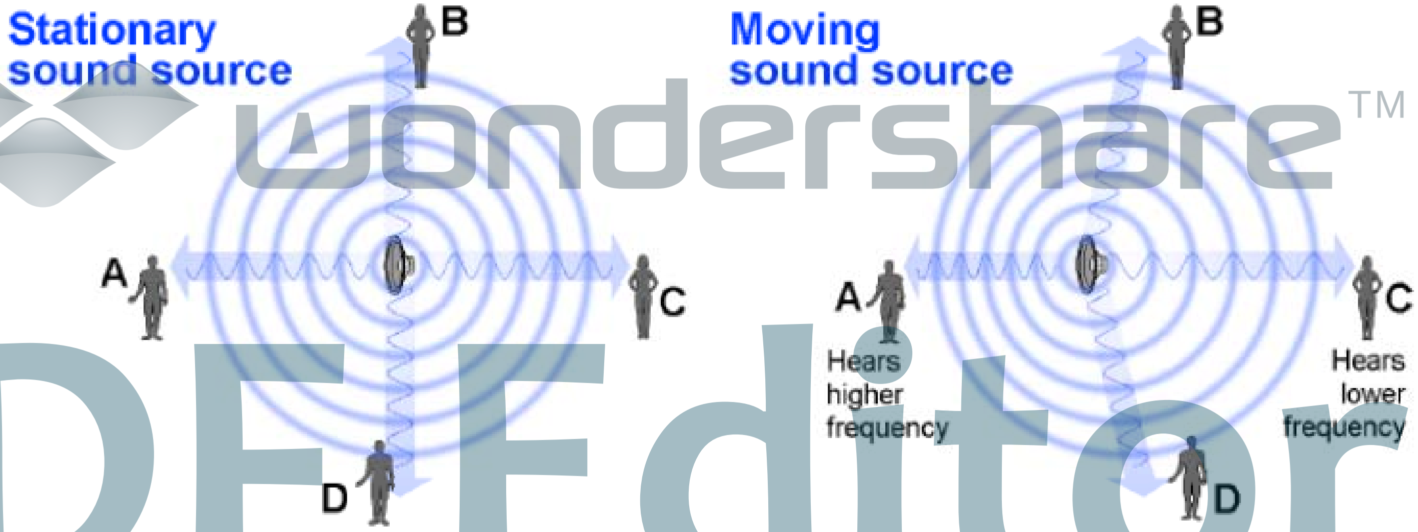
(b) $I = \dfrac{\Delta P_{\max}^2}{2\rho v}$, so

$$\Delta P_{\max} = \sqrt{2\rho v I} = \sqrt{2\left(1.20\ \text{kg/m}^3\right)\left(343\ \text{m/s}\right)\left(1.00\times10^{-5}\ \text{W/m}^2\right)}$$

$$\Delta P_{\max} = \boxed{90.7\ \text{mPa}}$$

The Doppler effect

- The shift in frequency caused by motion is called the **Doppler effect**.
- It occurs when a sound source is moving at speeds less than the speed of sound.



- That is, the observed frequency is ***increased*** whenever the source is moving toward the observer.
- When the source moves away from a stationary observer, as is the case for observer B in Figure , the observer measures a wavelength λ' that is *greater* than λ and hears a ***decreased*** frequency:

$$f' = \left(\frac{v}{v + v_S}\right) f \qquad \text{(source moving away from observer)}$$

Finally, we find the following general relationship for the observed frequency:

$$f' = \left(\frac{v + v_O}{v - v_S}\right) f$$

Example

- A submarine (sub A) travels through water at a speed of 8.00 m/s, emitting a sonar wave at a frequency of 1 400 Hz. The speed of sound in the water is 1 533 m/s. A second submarine (sub B) is located such that both submarines are traveling directly toward one another. The second submarine is moving at 9.00 m/s.
- Find the Doppler-shifted frequency as the two submarines approach each other?

Solution

$$f' = \left(\frac{v + v_O}{v - v_S}\right) f$$

$$= \left(\frac{1\,533\,\mathrm{m/s} + (+9.00\,\mathrm{m/s})}{1\,533\,\mathrm{m/s} - (+8.00\,\mathrm{m/s})}\right)(1\,400\,\mathrm{Hz}) = 1\,416\,\mathrm{Hz}$$

- What frequency is detected by an observer riding on sub B as the two submarines recede from each other?

$$f' = \left(\frac{v + v_O}{v - v_S}\right) f$$

$$= \left(\frac{1\,533\ \mathrm{m/s} + (-9.00\ \mathrm{m/s})}{1\,533\ \mathrm{m/s} - (-8.00\ \mathrm{m/s})}\right)(1\,400\ \mathrm{Hz}) = 1\,385\ \mathrm{Hz}$$

(c) While the subs are approaching each other, some of the sound from sub A will reflect from sub B and return to sub A. If this sound were to be detected by an observer on sub A, what is its frequency?

Answer : The sound of apparent frequency 1 416 Hz found in part (A) will be reflected from a moving source (sub B) and then detected by a moving observer (sub A). Thus, the frequency detected by sub A is

$$f'' = \left(\frac{v + v_O}{v - v_S}\right) f'$$

$$= \left(\frac{1\,533\ \text{m/s} + (+8.00\ \text{m/s})}{1\,533\ \text{m/s} - (+9.00\ \text{m/s})}\right)(1\,416\ \text{Hz}) = 1\,432\ \text{Hz}$$

QUIZ

Standing at a crosswalk, you hear a frequency of 560 Hz from the siren of an approaching ambulance. After the ambulance passes, the observed frequency of the siren is 480 Hz. Determine the ambulance's speed from these observations.

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$$= \boxed{26.4\ \text{m/s}}$$

Approaching ambulance: $$f' = \frac{f}{(1 - v_S/v)}$$

Departing ambulance: $$f'' = \frac{f}{(1-(-v_S/v))}$$

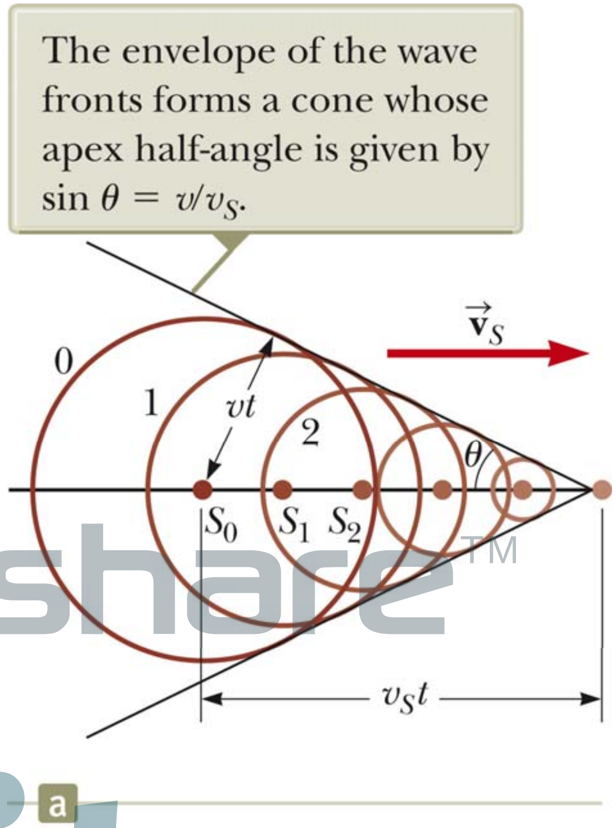
Since $f' = 560$ Hz and $f'' = 480$ Hz $$560\left(1 - \frac{v_S}{v}\right) = 480\left(1 + \frac{v_S}{v}\right)$$

$$1\,040\frac{v_S}{v} = 80.0$$

$$v_S = \frac{80.0(343)}{1\,040} \text{ m/s} = \boxed{26.4 \text{ m/s}}$$

Shock Waves and Mach Number

- The speed of the source can *exceed* the speed of the wave.
- The envelope of these wave fronts is a cone whose apex half-angle is given by sin $\theta = v/v_{S.}$
  - This is called the *Mach angle.*
- The ratio v_s / v is referred to as the *Mach number* .
- The relationship between the Mach angle and the Mach number is


The envelope of the wave fronts forms a cone whose apex half-angle is given by sin $\theta = v/v_S$.

$$\sin\theta = \frac{vt}{v_s t} = \frac{v}{v_s}$$

shock waves

The speed of sound depends primarily on the fluid temperature around it and is given as

$$v = \sqrt{\gamma RT}$$

where T is the temperature (Kelvin), R is the gas constant of fluid and γ is the adiabatic index of the gas (that is the ratio of specific heats of a gas at constant pressure and volume).

- For most calculations, standard air conditions are assumed and a value of γ =1.4 and R = 287 J/(kg K) are used.

$$\therefore M = \frac{v_s}{\sqrt{\gamma R T}}$$

Worked Example

- ***Determine the velocity of a bullet fired in the air if the Mach angle is observed to be 30° . Given that the temperature of the air is 22° C Take γ = 1.4 and R = 287.43 J/kg.K***

T = 273.15 +22 = 295.15 K

Sonic velocity =

$$\sqrt{\gamma RT} = \sqrt{(1.4)(287.4)(295.15}$$

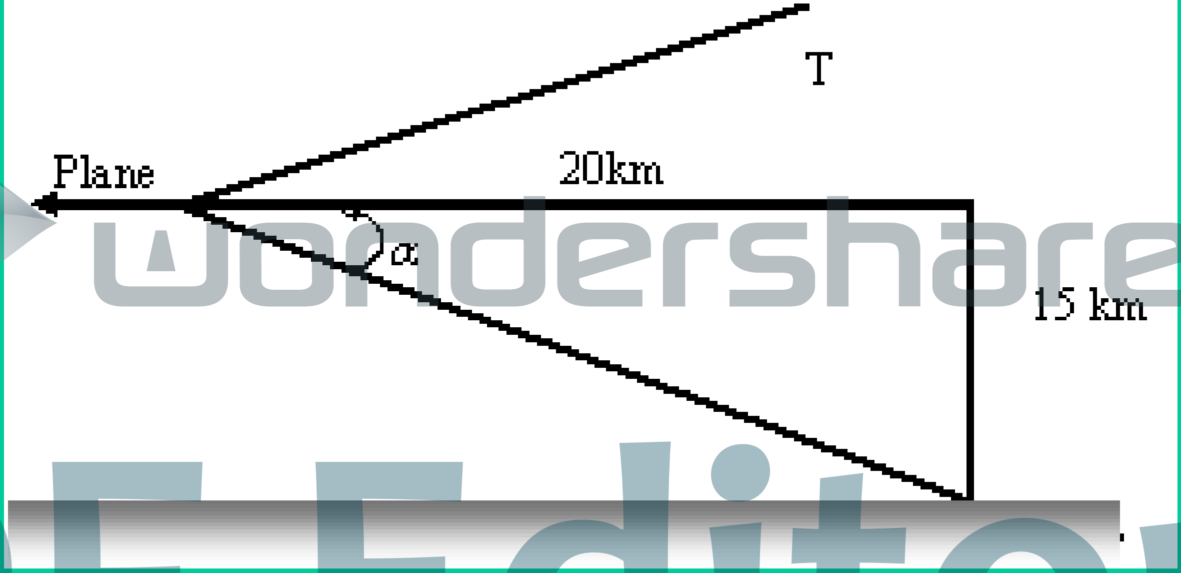
= 344.6 m/s

For the Mach cone, Sin α = $\frac{1}{M} = 0.5 \quad \therefore M = 2.0$

∴Bullet velocity = (2.0) (344.6 m/s) = **689.2 m/s**

Worked Example

An observer on the ground hears the sonic boom of a plane 15km above when the plane has gone 20km ahead of him. Estimate the speed of flight of the plane.



$$\tan \alpha = \frac{15\,km}{20\,km} = 0.75$$

$$\alpha = 36.87^\circ$$

$\sin 36.87^\circ = 0.6 = 1/M$

$M = 1.67$

The plane must be flying at a supersonic speed corresponding to a local mach number of 1.67.

Waves on a String, Harmonic Series

- The **fundamental frequency** corresponds to $n = 1$.
  - It is the lowest frequency, f_1
- The frequencies of the remaining natural modes are integer multiples of the fundamental frequency.
  - $f_n = nf_1$
- Frequencies of normal modes that exhibit this relationship form a **harmonic series.**
- The normal modes are called **harmonics.**

- **Resonance.**
  - All elastic objects have natural frequencies of vibration that are determined by the materials they are made of and their shapes.
  - When energy is transferred at the natural frequencies, there is a dramatic increase of amplitude called **resonance**.
  - The natural frequencies are also called **resonant frequencies**.

- **Resonance** – when a FORCED vibration matches an object’s natural frequency thus producing vibration, sound, or even damage

QUIZ

A train is moving parallel to a highway with a constant speed of 20.0 m/s. A car is traveling in the same direction as the train with a speed of 40.0 m/s. The car horn sounds at a frequency of 510 Hz, and the train whistle sounds at a frequency of 320 Hz. (a) When the car is behind the train, what frequency does an occupant of the car observe for the train whistle? (b) After the car passes and is in front of the train, what frequency does a train passenger observe for the car horn?

QUIZ

1. Two waves in one string are described by the wave functions

$$y_1 = 3.0\cos(4.0x - 1.6t)$$

and

$$y_2 = 4.0\sin(5.0x - 2.0t)$$

where y and x are in centimeters and t is in seconds. Find the superposition of the waves $y_1 + y_2$ at the points (a) $x = 1.00$, $t = 1.00$, (b) $x = 1.00$, $t = 0.500$, and (c) $x = 0.500$, $t = 0$.

$y = y_1 + y_2 = 3.00\cos(4.00x - 1.60t) + 4.00\sin(5.0x - 2.00t)$ evaluated at the given x values.

(a) $x = 1.00,\ t = 1.00$ $\quad y = 3.00\cos(2.40\text{ rad}) + 4.00\sin(+3.00\text{ rad}) = \boxed{-1.65\text{ cm}}$

(b) $x = 1.00,\ t = 0.500$ $\quad y = 3.00\cos(+3.20\text{ rad}) + 4.00\sin(+4.00\text{ rad}) = \boxed{-6.02\text{ cm}}$

(c) $x = 0.500,\ t = 0$ $\quad y = 3.00\cos(+2.00\text{ rad}) + 4.00\sin(+2.50\text{ rad}) = \boxed{1.15\text{ cm}}$

(a) We have $\lambda = \dfrac{v}{f}$ and f is the same for all three waves. Since the speed is smallest in air, λ is smallest in air. It is larger by $\dfrac{1\,493\ \text{m/s}}{331\ \text{m/s}} = \boxed{4.51\ \text{times}}$ in water and by $\dfrac{5\,950}{331} = \boxed{18.0\ \text{times in iron}}$.

(b) From $I = \dfrac{1}{2}\rho v \omega^2 s_{\max}^2$; $s_{\max} = \sqrt{\dfrac{2I_0}{\rho v \omega_0^2}}$, $s_{\max}$ is smallest in iron, larger in water by $\sqrt{\dfrac{\rho_{\text{iron}} v_{\text{iron}}}{\rho_{\text{water}} v_{\text{water}}}} = \sqrt{\dfrac{7\,860 \cdot 5\,950}{1\,000 \cdot 1\,493}} = \boxed{5.60\ \text{times}}$, and larger in air by $\sqrt{\dfrac{7\,860 \cdot 5\,950}{1.29 \cdot 331}} = \boxed{331\ \text{times}}$.

(c) From $I = \dfrac{\Delta P_{\max}^2}{2\rho v}$; $\Delta P_{\max} = \sqrt{2I\rho v}$, $\Delta P_{\max}$ is smallest in air, larger in water by $\sqrt{\dfrac{1\,000 \cdot 1\,493}{1.29 \cdot 331}} = \boxed{59.1\ \text{times}}$, and larger in iron by $\sqrt{\dfrac{7\,860 \cdot 5\,950}{1.29 \cdot 331}} = \boxed{331\ \text{times}}$.

(d)

$$\lambda = \frac{v}{f} = \frac{v2\pi}{\omega} = \frac{(331\ \text{m/s})2\pi}{2\,000\ \pi/\text{s}} = \boxed{0.331\ \text{m}}\ \text{in air}$$

$$\lambda = \frac{1\,493\ \text{m/s}}{1\,000/\text{s}} = \boxed{1.49\ \text{m}}\ \text{in water} \qquad \lambda = \frac{5\,950\ \text{m/s}}{1\,000/\text{s}} = \boxed{5.95\ \text{m}}\ \text{in iron}$$

$$s_{\max} = \sqrt{\frac{2I_0}{\rho v \omega_0^2}} = \sqrt{\frac{2\times10^{-6}\ \text{W/m}^2}{(1.29\ \text{kg/m}^3)(331\ \text{m/s})(6\,283\ 1/\text{s})^2}} = \boxed{1.09\times10^{-8}\ \text{m}}\ \text{in air}$$

$$s_{\max} = \sqrt{\frac{2\times10^{-6}}{1\,000(1\,493)}}\,\frac{1}{6\,283} = \boxed{1.84\times10^{-10}\ \text{m}}\ \text{in water}$$

$$s_{\max} = \sqrt{\frac{2\times10^{-6}}{7\,860(5\,950)}}\,\frac{1}{6\,283} = \boxed{3.29\times10^{-11}\ \text{m}}\ \text{in iron}$$

$$\Delta P_{\max} = \sqrt{2I\rho v} = \sqrt{2\left(10^{-6}\ \text{W/m}^2\right)\left(1.29\ \text{kg/m}^3\right)331\ \text{m/s}} = \boxed{0.029\,2\ \text{Pa}}\ \text{in air}$$

$$\Delta P_{\max} = \sqrt{2\times10^{-6}(1\,000)1\,493} = \boxed{1.73\ \text{Pa}}\ \text{in water}$$

$$\Delta P_{\max} = \sqrt{2\times10^{-6}(7\,860)(5\,950)} = \boxed{9.67\ \text{Pa}}\ \text{in iron}$$